Predicting Phosphorus Losses

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Background

In July 2003, the city of Tulsa, OK reached an agreement with six Arkansas poultry integrators and the city of Decatur to reduce P loading into the Lake Eucha-Spavinaw reservoir complex. As part of the agreement, poultry growers in the watershed were forbidden from land application of litter until a new phosphorus index (P-Index) could be developed and used in the watershed in both states. The court specified that the P-Index should be designed to produce a numerical risk for each field. The P-Index was to be developed jointly by scientists from Oklahoma State University (OSU) and the University of Arkansas (UA). The deadline was 1 January, 2004. Scientist at OSU and UA could not agree on a common approach within the time period and submitted separate approaches. Two questions have arisen in regards to predicting P losses: 1) how accurately can indices or models be used to predict the long-term relative risk of P loss or actual P loss at the edge of a field and 2) what is the need for long-term monitoring of edge-of-field P loss. In this section, we discuss how modeling can and should be used in predicting P losses in the Eucha-Spavinaw watershed, but the discussion is applicable to watersheds throughout the nation.

Edge-of-Field P Loss Predictions

There are some similarities between the way scientists at OSU and UA have approached predicting P losses in the Lake Eucha-Spavinaw watershed (Table 1). Both groups are using the same spatial scale which is field-scale. UA scientists are using a P-Index approach to estimate a relative risk (Daniel, 2004). The P-Index is based on the previously developed Arkansas P-Index for Pastures (DeLaune et al., 2004a) and the new P-Index is called the Eucha/Spavinaw P-Index (ESPI). It considers risk from source factors, transport factors, and best management practices (BMPs) and multiplies these to obtain an overall risk index (the higher the index, the higher the risk). Runoff risk is estimated based on the curve number and slope. Erosion risk is estimated using the Revised Universal Soil Loss Equation. The overall risk is modified based on the time of manure application. ESPI is designed to be simple and easy to use, especially for managers working in the field. It accounts for an extensive list of BMPs including streamside buffers and fencing cattle out of streams. The final output is a rating of low, medium, high, or very high risk for P movement beyond the edge of the field.

Scientists at OSU developed a P-Index using a modified version of the Soil Water Assessment Tool (SWAT) (Arnold et al., 1998; Neitsch et al., 2002). SWAT is designed for use at the scale of a watershed. The modified program is called the Phosphorus Pasture Management (PPM) Calculator and it estimates the average annual and monthly P loss at the edge of a field (Storm et al., 2004). The PPM Calculator runs on a daily time step and simulates plant growth and nutrient uptake, grazing, fertilizer and manure applications, erosion (based on the Modified Universal Soil Loss Equation), and runoff (based on the curve number approach). No predictions are made beyond the edge-of-field (there is no channel routing of sediment or P).

Like the ESPI, it is designed to be simple and easy to use in the field. A user interface contains a series of input blocks for entering readily available inputs such as STP and monthly stocking rates. Since SWAT is a watershed-scale model, it requires specification of a large number of parameter values. In the PPM Calculator, nine hydrologic parameters that can't be expected to be known by field users were determined using calibration in a representative watershed and given fixed values. These include parameters related to soil evaporation, percolation to groundwater, and curve number adjustments. The PPM Calculator requires specification of a "P allocation threshold" in lb/acre-yr as an input and one can test the effect of different thresholds on field-scale P losses. Future work will include adding more BMPs such as buffer strips and alum treatment, a delivery ratio that will extend P loading to receiving water bodies, economics, and row crop and small grain fields.

Both groups are using the same temporal scale which is a long-term multi-year average. The ESPI approach developed by UA scientists estimates a risk for average annual P loss. The PPM Calculator runs SWAT at a daily time step with a 15-year weather record for the Lake Eucha-Spavinaw basin and then calculates the annual and monthly averages.

In our opinion, accurately predicting P loss or relative risk at these spatial and temporal scales (long-term and edge-of-field) is an appropriate goal given the state of the science. A limited number of studies have shown the P-Index approach can identify fields with a high risk for P loss at these scales. Sharpley (1995) tested a P-Index approach on 30 grassed and cropped fields in the Southern Plains where long-term P losses had been measured. There was a good relationship between the P-Index and the log of the total P loss (r^2 = 0.70). DeLaune et al. (2004b) compared a P-Index to P concentrations in small plots receiving simulated rainfall and to annual P losses from two 0.4-ha fields. The P-Index was correlated with dissolved reactive P (DRP) concentrations in runoff from small plots (r^2 = 0.66) and annual P loss from the fields (r^2 = 0.83). Harmel et al. (2005) evaluated P-indices from TX, AR, and IA using three years of measured data from Riesel, TX, and found relatively poor agreement between the measured P losses and P-Index ratings ($r^2 \leq 0.31$). The field conditions were cultivated row crops or grassland receiving either poultry litter or inorganic fertilizers, which, as noted by the authors, was beyond the limits of some P-index intended applications. However, r^2 values improved to as high as 0.90 when models were adjusted for measured sediment losses.

A limited number of studies have shown that dynamic models are also reasonably accurate at these scales. Storm et al. (2004) have compared the PPM Calculator to data from a study by Edwards et al. (1994) on four fields (ranging in size from 0.56 to 1.46 ha) in the Illinois River watershed in Arkansas. Runoff was measured under natural rainfall for 33 months. Half of fields received manure and were stocked with cattle and half had no cattle or manure and received fertilizer. The observed and predicted P loads for each field are shown in Table 2. The relative error ranged from 12 to 66%.

Pierson et al. (2001a) used the Erosion Productivity and Impact Calculator (EPIC) to predict event and annual runoff and P loads from six paddocks in the Piedmont region of Georgia. The paddocks ranged in size from 0.72 to 0.79 ha. All of the paddocks received broiler litter and were grazed. The relationship between predicted and observed DRP was relatively poor on an event basis (r^2 = 0.42) but stronger on an annual basis (r^2 = 0.56). Edwards et al. (1994) also found reasonable correlation (r^2 = 0.80) between EPIC predictions and observed annual P losses from pastures receiving either inorganic P fertilizer or poultry litter.

Even at these scales (field and annual), there are gaps in our scientific knowledge about P processes, be they implemented in P indices or dynamic models. One question is where are the areas in a field that produce runoff? A study by Gburek and Sharpley (1998) on the same small watershed in Pennsylvania reported in Srinivasan et al. (2005) used small sensors to detect the areas where runoff occurred. They estimated that only 14% of the watershed (mostly low-lying areas near the stream) produced runoff. Chaubey et al. (2004) used similar devices to identify runoff areas in a field in Arkansas and found that subsurface features caused runoff in the mid-slope region. In Iowa, they have recognized that there are major differences in risk of P loss within fields (Mallarino et al., 2001). Nutrient management planners can zone fields for P index calculations based on characteristics relevant to P loss. Another question is the effectiveness of common best management practices (BMPs) in reducing P losses. The P subroutines in models such as SWAT were developed for EPIC nearly thirty years ago and have not been improved much since, despite advances in research.

In our opinion, watershed-scale predictions of loadings to lakes are not reliable unless extensive, site-specific calibration is used. The same can be said for short-term (daily) predictions at the edge-of-field scale. These types of predictions remain in the research development stage. The capability to make predictions at this scale is, however, an appropriate long-term goal. US EPA policy is committed to a watershed approach (US EPA, 2005). It is also at this scale that the public and courts want answers. This is particularly true with P, where the primary concern is usually loading to lakes (the case in the Eucha Spavinaw watershed).

To make accurate predictions at the watershed and short-term scales, many research questions need to be answered (including those already mentioned regarding runoff areas and BMPs). One question is how long does the manure pool act as source of P separate from soil test P (STP) in farming systems where manure is not incorporated (the typical practice in the Eucha-Spavinaw watershed)? DeLaune et al. (2004a) showed that the manure pool dominated STP as a source for up to 14 days after application of broiler litter, but it is not known how much longer these pools remain separate. Vadas et al. (2004, 2005) have suggested modifications to existing models to account for these two pools. Another area that needs to be addressed is in-stream processes for P including interaction with suspended sediment, bed sediment, and aquatic biota. Dynamic watershed-scale models differ in the manner and number of processes included. Parameter values for these processes are especially difficult to determine. As a consequence, sources, sinks, and travel times for P in streams are largely unknown. Finally, we need to be able to put confidence limits on model predictions.

The approaches taken by scientists at UA and OSU have different strengths that would complement each other if combined. The strength of the P-Index approach is that it includes important field-scale processes such as P loss from a separate manure pool and BMPs, which are not currently part of SWAT. Also, the P-Index approach is relatively easy to develop for a given watershed in that calibration is not required. Weaknesses of this approach are that it is not easily expanded beyond the edge-of-field spatial scale and adjusted towards short-term time scales and that it predicts a relative risk instead of a P load, which is desired by the court. A weakness of the dynamic model approach (based on SWAT) is that it needs an updated P process that includes separate STP and manure pools and that accounts for BMPs. Another weakness is that some of the model parameters must be calibrated using data representative of the watershed in which it is to be applied. It's strengths are that it predicts a P load at average annual and average monthly intervals and has the potential to predict transport at the watershed-scale.

Long-term Monitoring of Edge-of-Field P Loss

Models of various forms and complexities, ranging from process-based models to simplistic empirical models, have proven useful for the advancement of scientific knowledge by the comparison of land management practices on resulting water quality, runoff, and crop production. Models have also been valuable tools for educating the general public on issues related to P loss from agricultural lands and its impact on water quality. Many of these models have undergone scientific scrutiny and varying levels of validation to ensure the integrity of information gleaned from their use. These review and validation measures have proven satisfactory for the intended uses of the models; education and advancement of scientific understanding. Recently, field-scale P loss predictions from various models have been used to regulate individual producers. Models initially designed for education and scientific studies of relative impact may be well suited for broader applications, including legal regulation. However, caution must be used when models are applied for these expanded purposes. For example, because of the potential for model results to inflict direct economic harm on individual producers, models should undergo additional validation and subsequent refinements prior to regulatory application.

A major obstacle to extensive model validation is the lack of complete datasets that can be used for validation. Many of the datasets used for the development of models and study of P transport mechanisms have been produced under simulated rainfall (Edwards et al., 1995; Sauer et al., 2000; Kleinman et al., 2002). Rainfall simulation studies are helpful in determining relative differences in controlled settings, investigating nutrient loss processes, and isolating effects of individual variables. Although relative P loss trends observed under simulated rainfall are also observed in field studies, the predictive relationships developed from simulated rainfall are not always directly transferable to natural rainfall conditions (Cox and Hendrix, 2000). Because of the differences between P losses observed under simulated rainfall vs. natural rainfall, models should be validated with datasets derived from natural rainfall studies. Datasets that quantify P losses from both natural rainfall and irrigation-induced runoff and erosion should be used to validate models predicting P losses from irrigated agriculture. Phosphorus loss from agricultural fields acquired under natural rainfall is subject to considerable variability during and among runoff events as well as between sites (Harmel et al., 2004; Kurz et al., 2005). Therefore, long-term datasets from a variety of sites are particularly useful to capture this variability. Furthermore, in-stream processes (including biological uptake, mineralization, adsorption, desorption, and sedimentation) alter nutrient forms, transport, and eventual impact on larger receiving waters. Datasets that include both edge-of-field P losses and down-stream watershed P losses are uniquely suited to assess the relationship between P losses at the field edge and P delivery to sensitive water bodies.

Because field-scale studies quantifying P losses under natural rainfall require large land areas, have high equipment and personnel expenses, and generate large numbers of samples, there are relatively few datasets available (Harmel et al., 2004). Furthermore, there are even fewer datasets quantifying both field-scale P losses and down-stream watershed-scale P losses. However, several research locations have quantified or are currently monitoring field-scale P losses. Selected characteristics from these research locations and associated publications reporting measured P losses appear in Table 3. These studies have focused on P losses from fields receiving either poultry litter or inorganic fertilizers, for the most part. The wide range of P losses reported by these studies indicates a need for additional investigation of factors contributing to observed losses. Further research is needed to incorporate a wider range of cropping practices, P sources, and landscape/climate factors.

Studies listed in Table 3 can serve as examples of experimental design and sampling protocols for future studies. Ideally, future edge-of-field studies should be nested within larger watershed studies to allow for a more robust validation of the model predictions, as demonstrated at the Riesel, TX research location (Harmel et al., 2004). If possible, watershed studies should be set up in a paired design to allow for statistically sound data analysis independent of model results (Spooner and Line, 1993). Collection of both flow rate and water quality data is vital; however, recommended data collection protocols depend on field size and location, runoff intensity and volume, sampling equipment, sample collection and processing capabilities, and research objectives. Therefore, these variables should be carefully considered so that flow monitoring and sampling procedures are appropriately designed to meet research objectives (Harmel et al., 2003). Surface runoff from natural rainfall and irrigation events should be measured, ideally with a pre-calibrated flow control structure, and recorded on a 2-15 minute interval depending on watershed size. Water quality samples should be collected frequently during each runoff event. Sampling infrequently or only selected storms provides less useful data and introduces considerable uncertainty into annual P load estimates (Harmel and King, 2005). At a minimum, collected water samples should be analyzed for total suspended solids, total P, and dissolved reactive P. Soil P concentration is an integral input in many models. Furthermore, datasets documenting management induced changes in soil P concentration offer another level of model validation for process-based models. Therefore, studies should closely monitor soil P concentration as well as document all field practices affecting soil P concentration and distribution. Because field-scale P loss is highly dependant on climate variability, studies should be conducted for a minimum of 4 to 5 years to capture variability and allow for statistical analysis of results from paired watersheds.

Position of SERA-17 on Modeling Phosphorus Losses

The Eucha Spavinaw watershed court case poses a number of vexing scientific issues on modeling P losses and has forced the scientific community in this region to address controversial policy issues. Based on our assessment, we make the following observations and recommendations regarding the science supporting P transport modeling:

- The two approaches for predicting P loss developed by scientists at OSU and at UA share a common spatial scale (edge-of-field) and temporal scale (annual or longer-term). They differ in that the UA approach predicts a relative risk for P loss and the OSU approach predicts a specific P loss.
- These are the appropriate scales for making predictions, given the current scientific understanding, and both approaches have been shown in a limited number of studies to provide reasonably accurate predictions.
- Making watershed-scale predictions of P loading to lakes or short-term (daily) P losses at the edge-of-field cannot be done reliably without extensive and site-specific calibration of watershed-scale models.
- The strengths of the P-Index approach are that it treats manure and soil P as separate sources, includes a number of BMPs, and is readily adapted to different watersheds. The strengths of the dynamic model approach are that it predicts a load rather than a risk and has the potential to predict loadings to a lake.

- Since the approaches taken by scientists at UA and scientists at OSU have complimentary strengths, the two groups are encouraged to strive for a common approach.
- Further research is needed to study P source and cropping system effects on edge-of-field P losses. Field-scale studies should be conducted under natural rainfall or irrigation conditions for greater than 3 years. USDA-ARS is particularly well suited to conducting such long-term studies.
- Preferably, long-term field-scale studies should be nested within watershed-scale studies to better evaluate the relationship between edge-of-field P loss and down-stream P inputs to sensitive water bodies. Datasets from these studies would be a valuable resource for model validation thereby allowing for extended model applications in the regulatory area.

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Table 1. A comparison of the P-Index (ESPI) and Dynamic Model (PPM Calculator) approaches.

Feature	P-Index Approach (ESPI)	Dynamic Model Approach (PPM Calculator)
Output	Risk of losing P	P load lost
Spatial Scale	Edge of field	Edge of field
Temporal Scale	Long-term annual average	Long-term annual and monthly averages
Estimation of runoff	Index based on NRCS curve number and slope	Daily runoff based on NRCS curve number
Soluble P concentration in runoff	Based on STP and adsorption coefficients from rainfall simulation studies and P solubility in manure	Based on soil labile P and adsorption coefficients; does not consider manure
Manure as a P source	Treats manure as a separate source of P	Does not treat manure as a separate source
Erosion	Based on RUSLE	Based on MUSLE
BMPs	Accounts for buffers, time of application and cattle access to streams (10% reduction in risk if cattle do not have access)	Accounts for time of application
Number of input parameters	Few	Many but most of these are pre-calibrated
Row crops	Does not address	Does not address
User interface	Easy to use in field	Easy to use in field

Table 2. Observed and predicted total P loads in four fields from two sites. Unmanaged fields (RU and WU) received litter and managed fields (RM and WM) received commercial N fertilizer Site WM received both litter and commercial N fertilizer. Observed loads were measured in a study by Edwards et al. (1994). The PPM Calculator was used to make the predictions of total P (Storm et al., 2004).

Field	Observed Total P	Predicted Total P	Relative Error
	kg/ha-yr		%
R Site Unmanaged (RU)	4.6	5.7	-25
R Site Managed (RM)	0.77	0.54	29
W Site Unmanaged (WU)	2.0	2.2	-12
W Site Managed (WM)	2.7	0.91	66

Table 3. Studies reporting edge-of-field phosphorus losses from natural rainfall (*adapted from:* Harmel et al., 2004).

Site location	Land use	Applied P sources	Dates	Area (ha)	P forms monitored at field edge†	Mean annual P loss (kg ha^{-1})	Down-stream monitoring	Published data
Iowa	corn	poultry manure	1998–2000	0.40	PO_4-P	0.2–0.3‡	no	Chinkuyu et al., 2002
Arkansas	grazed fescue	poultry manure poultry litter none	1992–1994	1.06–1.23	PO_4-P	1.58–4.34‡	no	Edwards et al., 1996
Alabama	corn-winter rye	poultry litter inorganic fertilizer	1991–1993	0.11	sediment P, dissolved P, total P	0.99–2.42	no	Hall (1994) Wood et al., 1999
Georgia	grazed fescue	poultry litter cattle manure	1995–1996	0.75	DRP§	7.40‡	no	Pierson et al., 2001b Kuykendall et al., 1999
Arkansas	cotton	poultry litter none	1996–1998	0.60	PO_4-P, total P	3.0	no	Vories et al., 2001
Georgia	Bermuda-fescue	poultry litter composted litter	1995–1996	0.45	DRP, total P	0.1–0.4	no	Vervoort et al., 1998
Texas	corn pasture	poultry litter inorganic fertilizer	1984–1989 2000–2003	1.2–8.4	dissolved P, sediment-bound P	0.15–6.25	yes	Chichester and Richardson, 1992 Harmel et al., 2004 Harmel et al., 2005
Arkansas	fescue	poultry litter alum-amended litter	1995–2000	0.405	soluble reactive P, total P	0–3.1	no	Moore et al., 2000 DeLaune et al., 2004b
Missouri	corn/soybean rotation	inorganic fertilizer	1991–1997	1.65–4.44	total P	0.13–0.18	no	Udawatta et al., 2004
Ireland	grazed pasture	inorganic fertilizer	1996-1998	0.46–1.54	DRP, total dissolved P, total P	0.70–4.76‡	no	Kurz et al., 2005
Oklahoma	native grassland wheat	inorganic fertilizer	1977-1992	1.6	total P	0.20–2.98	no	Sharpley, 1995

† P forms as reported in published data
‡ Does not represent total P losses due to lack of data
§ dissolved reactive phosphorus